Unitarity of CKM Matrix: |Vud| *from neutron decay*

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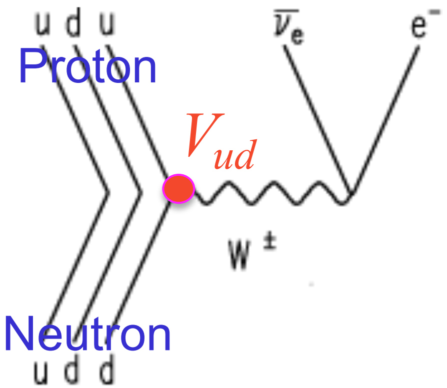
$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} {\color{red}V_{ud}} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak states

CKM mixing matrix

Mass eigenstates



LOI: Tanmoy Bhattacharya, Steven Clayton, Vincenzo Cirigliano, Rajan Gupta, Takeyasu Ito, Yong-Chull Jang, Mark Makela, Emanuele Mereghetti, Chris Morris, Santanu Mondal, Sungwoo Park, Alexander Saunders, Boram Yoon, Albert Young

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Some Relevant References

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Resolving V_{ud} -SM disagreement, V_{ud} from $0^+ \rightarrow 0^+$ nuclear *Versus* neutron decay

$$\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$$

	$\|V_{ud}\|$	$\|V_{us}\|$	$\|V_{ub}\|$	Δ_{CKM}
PDG 2020	0.97370(14) [from nuclear decay measurements]	0.2243(8)	$3.82(24)\times10^{-3}$	$-15.8(4.5)\times10^{-4}$

3-σ disagreement with the Standard Model

$$|V_{ud}|^2 = \frac{5099.3(4)\mathrm{s}}{\tau_n(1+3g_A^2)(1+RC)}$$

Neutron Decay
See Czarnecki, et al

τ_N: neutron lifetime (UCNτ+)
g_A: neutron axial charge (UCNA+)
RC: radiative corrections (Lattice QCD)

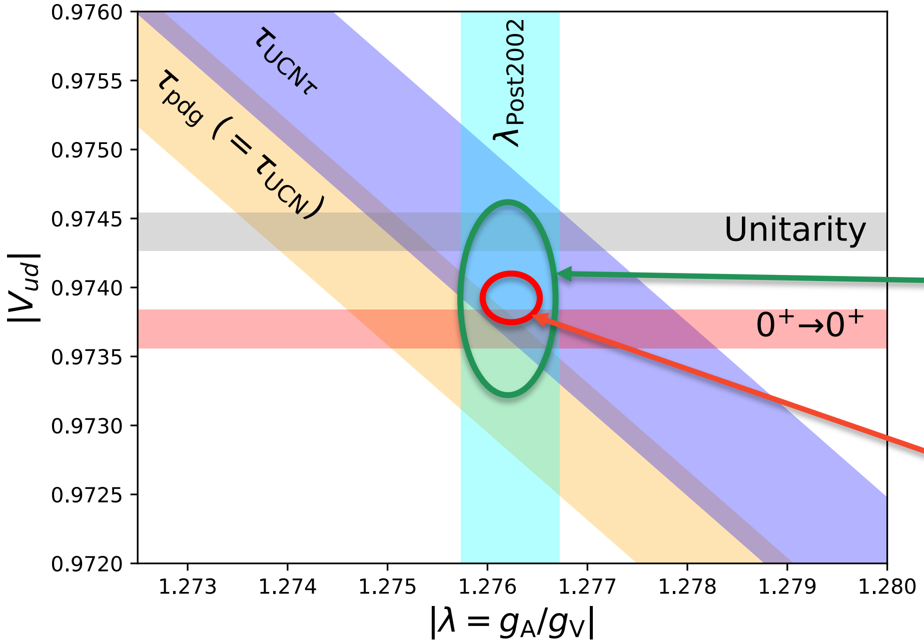
Goal: Reduce uncertainty in Δ_{CKM} from (18) to (5) in neutron decay.
Neutron decay measurement is *clean* and the systematics are *independent*.

Improve neutron decay measurements to test CKM unitarity and expose possible BSM signal.

Neutron decay master formula:

$$|V_{ud}|^2 = \frac{5099.3(4)\mathrm{s}}{\tau_n(1+3g_A^2)(1+RC)}$$

Present experimental status



Present neutron β-decay uncertainty ellipse

Target uncertainty from neutron β-decay

Current Goal: extract V_{ud} from neutron β-decay with fully controlled uncertainties at the $\sim 2\times10^{-4}$ level

V_{ud} : Key to testing $\Delta_{CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1$

Current best measurement of $|V_{ud}|^2 = 0.94907(43)$ comes from superallowed $0^+ \to 0^+$ nuclear transitions

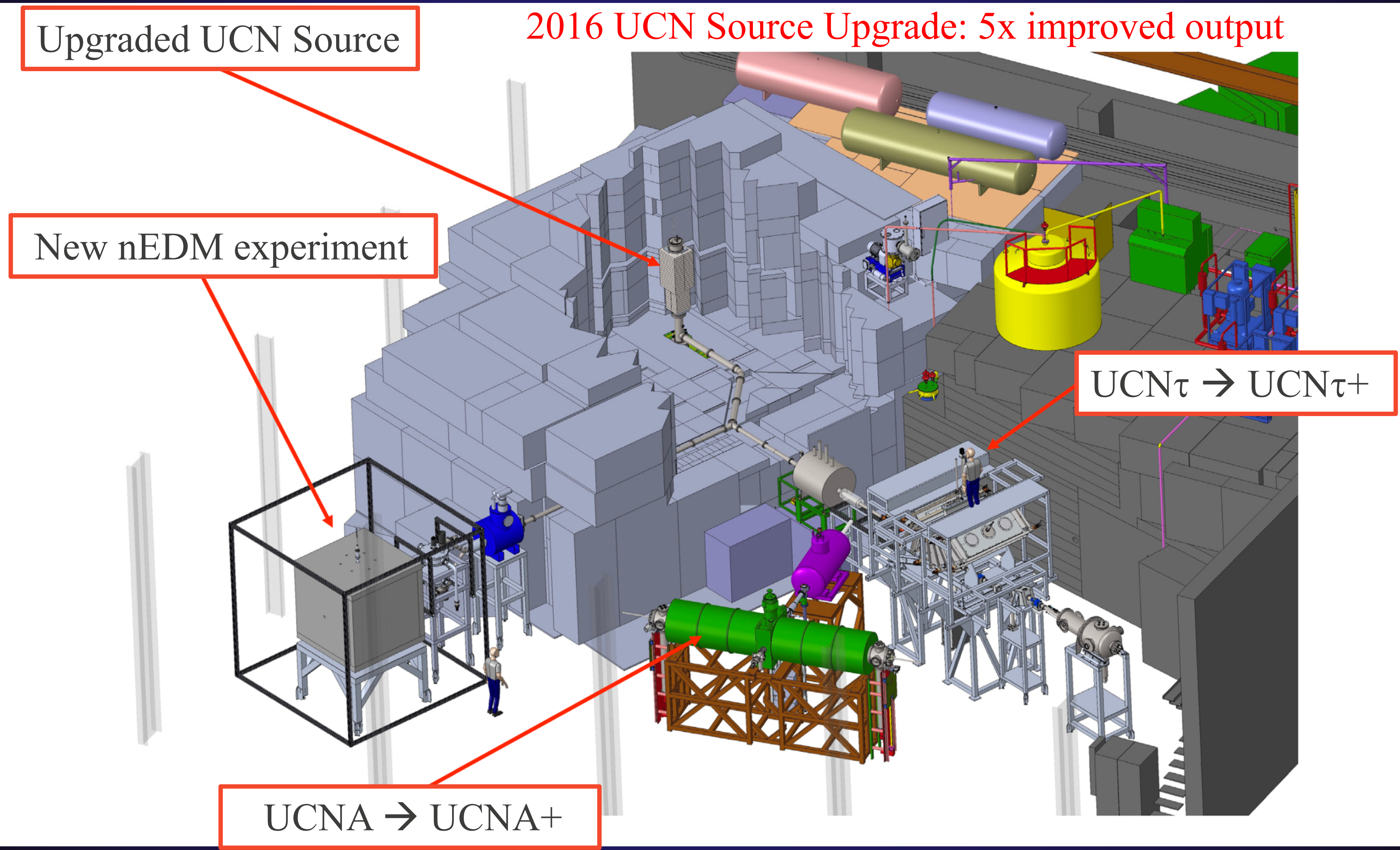
- Pure vector current transitions at tree level
- Beyond tree-level, axial current also contributes and radiative correction dominate uncertainty
- Different estimates of radiative corrections including nuclear interactions have significant impact on unitarity test, ie, Δ_{CKM} (2—4 σ)

V_{ud} from nucleon decay

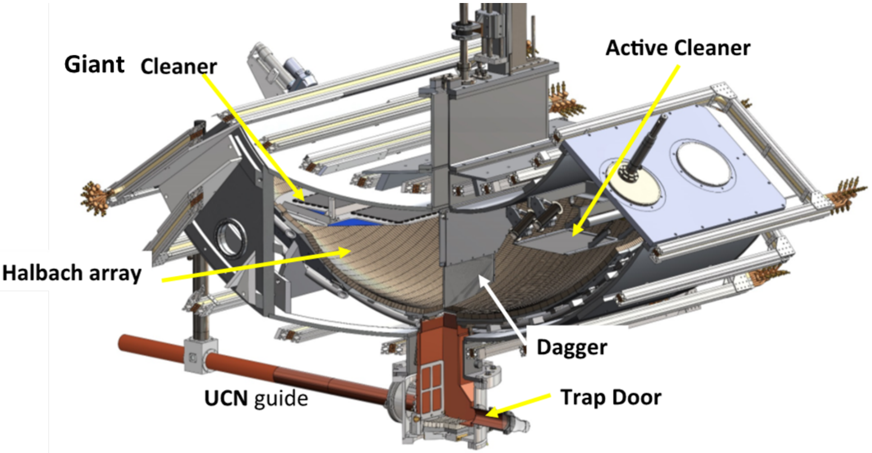
- Free of nuclear corrections
- Improve free neutron lifetime τ_n (UCNτ+) $\delta\tau_n \approx 0.3s \to 0.1s$
- Improve $\lambda = \frac{g_A}{g_V}$ (UCNA+) $\frac{\delta A}{A} \approx 0.1\%$
- Radiative corrections with lattice QCD $\lesssim 20\%$

LANL: World's Best UCN Source Feeds Multiple Experiments

2016 UCN Source Upgrade: 5x improved output

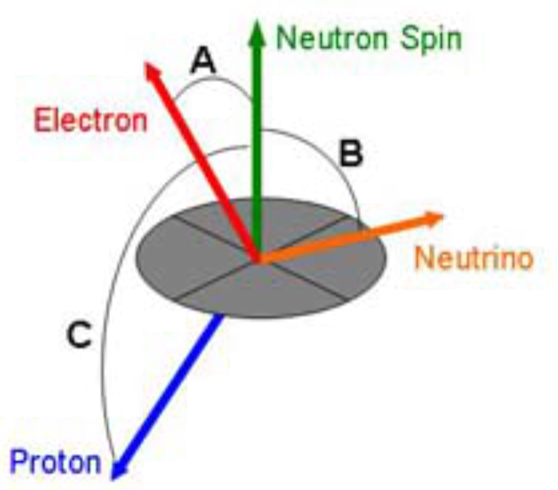


Through 3 key innovations, we can search for BSM physics beyond the reach of the LHC (>10 TeV)

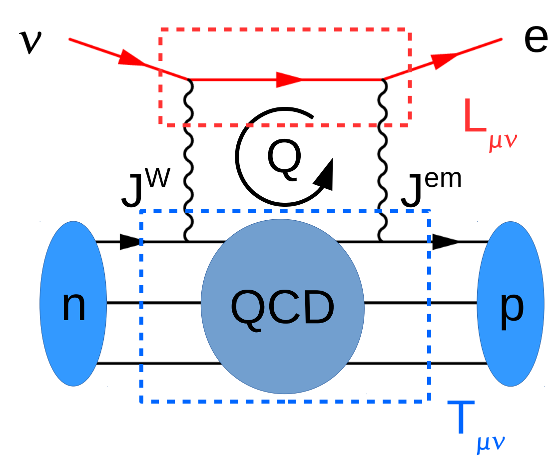


UCNτ+ to improve on UCNτ by 3×

- LANL is pursuing a complete measurement of V_{ud} using ultracold neutrons.
- Address the 3-sigma disagreement between current V_{ud} and SM value.

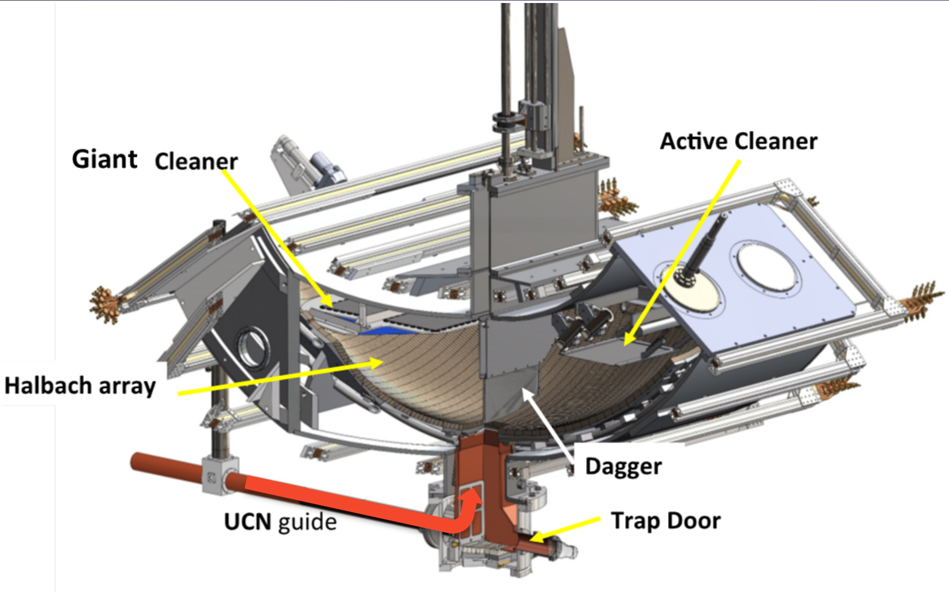


UCNA+ to improve sensitivity of UCNA by 3×

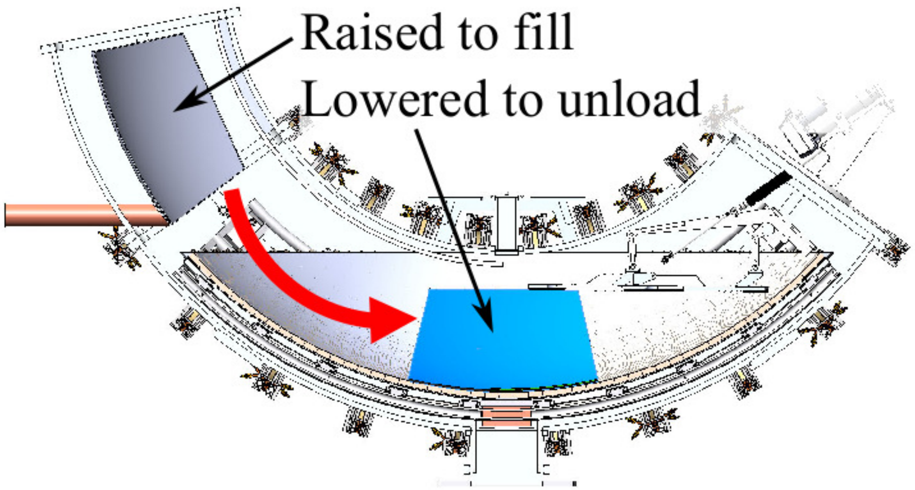


New Lattice QCD calculations will reduce theory uncertainty by 2-3x

UCNτ → UCNτ+ : Elevator Concept for 10× loading increase



~0.5% loading efficiency



~10X improvement

UCNτ:

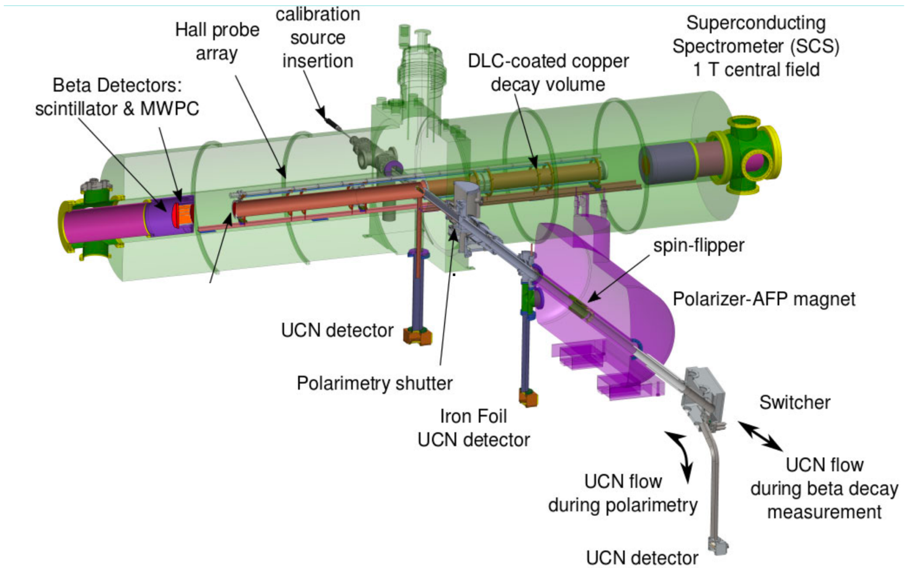
- World's best neutron lifetime measurement
- Only τ_n measurement with systematic correction smaller than uncertainty
- Ultimate reach is statistics limited
- Other experiments targeting 0.3sec in 5 yrs

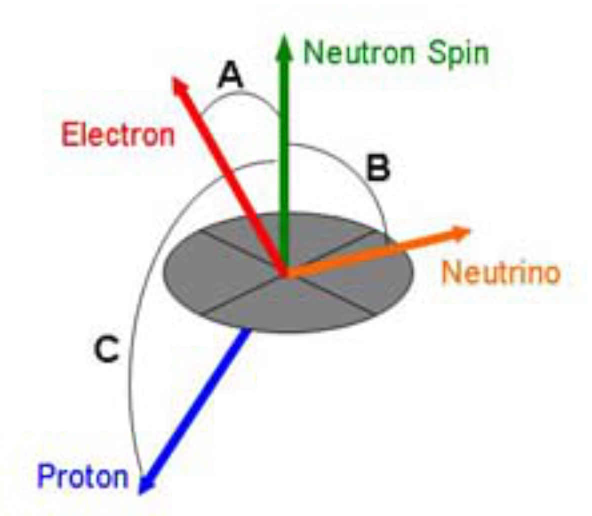
UCNτ+:

Develop new UCN loading using elevator to increase trapped UCN by >10×

Upgrade the main UCN detector for this higher rate

UCNA → UCNA+: Improve β-decay asymmetry by 3×





UCNA

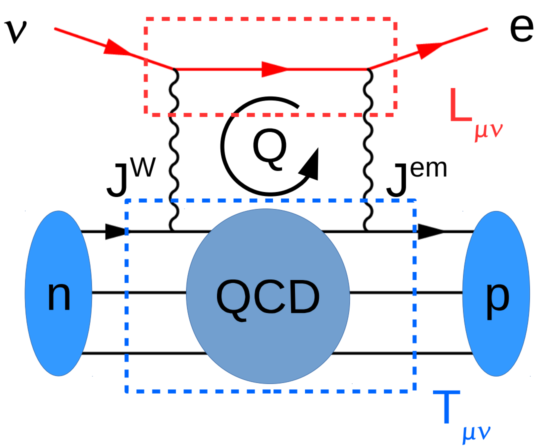
- World's only UCN-based neutron β-decay asymmetry experiment
- Experiment completed and published fully understood and documented systematic uncertainties.
- Final uncertainty was limited by performance of pre-upgrade UCN source.

UCNA+

- Upgraded UCN source performance enables 3x better reach
- Incorporate new silicon photomultiplier plastic scintillator readout
- Develop new precise calibration tools

Competition: Nab and PERC

LQCD calculations of radiative corrections
will impact many weak processes

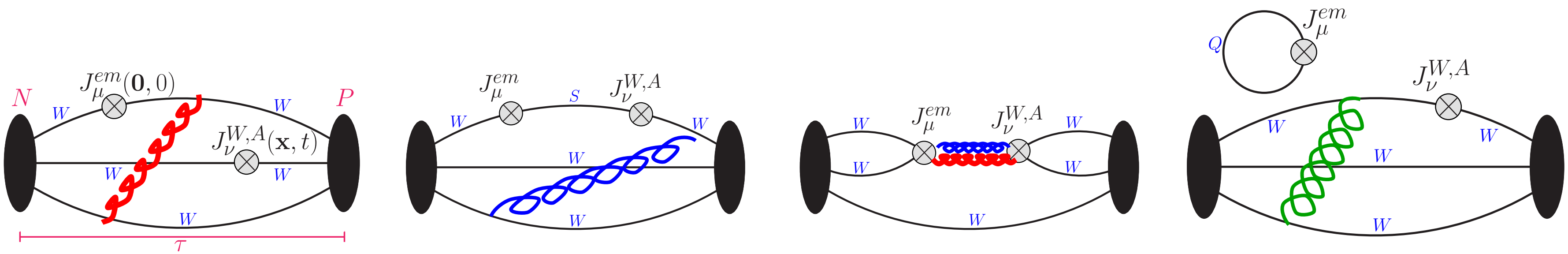


- Box diagram contributes only ~3% to decay rate but dominates uncertainty.
- The integral requires control over all virtual momenta:

low and **high**

(non-perturbative → lattice QCD) (perturbative → analytical)

Lattice QCD calculation of the γW **box diagram**



$$T_{\mu\nu}(Q) = \frac{1}{2}\int d^4x\, e^{iQx} \left\langle N_f(p)\right| T\left[J_\mu^{em}(0,0)\mathrm{J}_\nu^{\mathrm{WA}}(\vec{\mathrm{x}},\mathrm{t})\right]\left|N_i\,(p)\right\rangle$$

- 4-point function calculated as a function of the separation between the two space-time points (0,0) and (x,t) at which the currents are inserted
- Connected and disconnected diagrams

See Xu Feng et al. arXiv:2003.09798 → PRL 124 (2020) 192002

V_{ud} from neutron decay:
An opportunity to search for BSM physics

V_{ud} from neutron decay (no systematics due to nuclear corrections) requires

- UCNτ → UCNτ+ → Next Gen
- UCNA → UCNA+ → Next Gen
- Radiative Corrections: lattice QCD and effective field theory.

All three efforts are underway at LANL to resolve the V_{ud} – SM discrepancy.

<u>Synergistic calculations</u>

1) γW box diagram for Kaon decay for $|V_{us}|$
2) Semi leptonic form factors